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Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000

By R. A. HOUGHTON*, *The Woods Hole Research Center, PO Box 296, Woods Hole, MA 02543, USA*

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ABSTRACT

Recent analyses of land-use change in the US and China, together with the latest estimates of tropical deforestation and afforestation from the FAO, were used to calculate a portion of the annual flux of carbon between terrestrial ecosystems and the atmosphere. The calculated flux includes only that portion of the flux resulting from direct human activity. In most regions, activities included the conversion of natural ecosystems to cultivated lands and pastures, including shifting cultivation, harvest of wood (for timber and fuel) and the establishment of tree plantations. In the US, woody encroachment and woodland thickening as a result of fire suppression were also included. The calculated flux of carbon does not include increases or decreases in carbon storage as a result of environmental changes (e.g., increasing concentrations of CO_2, N deposition, climatic change or pollution). Globally, the long-term (1850–2000) flux of carbon from changes in land use and management released 156 PgC to the atmosphere, about 60% of it from the tropics. Average annual fluxes during the 1980s and 1990s were 2.0 and 2.2 PgC yr^{-1}, respectively, dominated by releases of carbon from the tropics. Outside the tropics, the average net flux of carbon attributable to land-use change and management decreased from a source of 0.06 PgC yr^{-1} during the 1980s to a sink of 0.02 PgC yr^{-1} during the 1990s. According to the analyses summarized here, changes in land use were responsible for sinks in North America and Europe and for small sources in other non-tropical regions. The revisions were as large as 0.3 PgC yr^{-1} in individual regions but were largely offsetting, so that the global estimate for the 1980s was changed little from an earlier estimate. Uncertainties and recent improvements in the data used to calculate the flux of carbon from land-use change are reviewed, and the results are compared to other estimates of flux to evaluate the extent to which processes other than land-use change and management are important in explaining changes in terrestrial carbon storage.

1. Introduction

The distribution of sources and sinks of carbon over the land surface is dominated by changes in land use. In the tropics, current rates of deforestation are responsible for large sources of carbon; in northern mid-latitudes past changes in land use explain much of the observed sink (Houghton, 1996, 1998; Houghton et al., 1999; Pacala et al., 2001).

*e-mail: rhoughton@whrc.org

Despite the importance of land-use change in dominating long-term net terrestrial fluxes of carbon, estimates of the annual flux are uncertain relative to other terms in the global carbon budget (Prentice et al., 2001). This paper presents the results of several new regional analyses of land-use change and extends a previous global estimate of carbon flux (Houghton, 1999) to the year 2000. The new data and the revised annual fluxes of carbon are available as a numerical data package through http://cdiac.ornl.gov/.

2. Methods

2.1. Overview of the approach

The methods are the same as reported by Houghton (1999). A book-keeping model (Houghton et al., 1983; Houghton and Hackler, 1995) was used to calculate net sources and sinks of carbon resulting from land-use change and management in nine world regions. Calculations were based on two types of data: rates of land-use change and per hectare changes in carbon storage that result from changes in land use and land management. Changes in land use are defined broadly to include the clearing of lands for cultivation and pastures, the abandonment of these agricultural lands, the harvest of wood, reforestation, afforestation and shifting cultivation. In the US we included wildfires (Houghton et al., 1999), because active policies of fire exclusion and fire suppression have affected carbon storage, and because data on annual areas burned were available.

The book-keeping model tracks the carbon in living vegetation, dead plant material, wood products and soils for each hectare of land cultivated, harvested or reforested. Rates of land-use change were generally obtained from agricultural and forestry statistics, historical accounts and national handbooks. Carbon stocks and changes in them following disturbance and growth were obtained both from field studies published in the ecological literature (to document biomass and soil carbon) and from forestry statistics and ecological and anthropological studies (to document the uses and half-lives of wood products). The data and assumptions used in the calculations reported here are more fully documented in Houghton (1999) and Houghton and Hackler (2001).

The calculated flux is not the net flux of carbon between terrestrial ecosystems and the atmosphere because the analysis does not consider ecosystems undisturbed by direct human activity. Rates of decay and rates of regrowth are defined in the model for different types of ecosystems and different types of land-use change, but they do not vary through time in response to changes in climate or concentrations of carbon dioxide. The processes explicitly included in the model are the ecological processes of disturbance and recovery, not the physiological processes of photosynthesis and respiration.

This new global estimate includes extensive revisions in five regions and extends the estimated annual fluxes of carbon through the 1990s in all regions. We revised the three major tropical regions (sub-Saharan Africa, Latin America and tropical Asia) with new and revised rates of deforestation and afforestation for the 1980s and 1990s (FAO, 2000; 2001b). The new estimates also include more extensive revisions for the US (Houghton et al., 1999) and China.

2.2. Major revisions

2.2.1. The tropics. In an earlier estimate, Houghton (1999) obtained rates of deforestation for Latin America and Africa from FAO's Forest Resources Assessment 1990 for Tropical Countries (FAO, 1993). For tropical Asia, Houghton and Hackler (1999) and Houghton (1999) used more recent estimates (FAO, 1997) that included the first half of the 1990s. The FAO (2000; 2001b) has subsequently published estimates of deforestation for the 1990s, which include revisions for the 1980s and the first half of the 1990s. We used these most recent estimates to calculate annual fluxes of carbon to the year 2000. According to these estimates, rates of deforestation increased after the 1980s in Asia and Africa and decreased in Latin America (FAO, 2000) (Table 1). The rate for the entire tropics was only 2.7% higher in the 1990s than the

Table 1. *Average annual rates of tropical deforestation and afforestation (10^3 ha yr^{-1}) (from FAO, 1993, 2000)*

	1981–1990		1991–2000	
	Deforestation	Afforestation	Deforestation	Afforestation
Africa	−4101	130	−5524	250
America	−7407	373	−4546	215
Asia[a]	−3922	2104	−5770	3225
Total	−15 430	2607	−15 840	3690

[a]Includes tropical Oceania.

1980s. Rates of establishment of tree plantations also increased, especially in tropical Asia.

2.2.2. North America. Re-analyses of the US (Houghton et al., 1999, 2000a; Houghton and Hackler, 2000) and, more crudely, Canada (this work) yielded estimates of flux different from the earlier estimate for North America (Houghton, 1999). In the re-analysis of the US we estimated fluxes for three processes not previously included: woody encroachment, 'thickening' of western pine forests from early fire suppression and gains in soil carbon as a result of changes in agricultural management. For the first two of these processes we constructed estimates of flux that we considered upper bounds. For the global estimate constructed here, we halved the upper bounds for these two processes to yield a more conservative central value. For the third process, subsequent work has shown that the accumulation of carbon in agricultural soils is much lower than we calculated (Pacala et al., 2001), and we eliminated that flux from the estimate included here. The result of these adjustments gave a net source for the US of 15 PgC over the period 1700–2000 and an average annual sink of 0.110 PgC yr^{-1} for the 1990s. The estimate is lower than initially calculated for the 1980s (0.15–0.35 PgC yr^{-1}) (Houghton et al., 1999).

For Canada, rates of agricultural expansion and contraction and rates of wood harvest were obtained from FAO (2001a) for the years 1991–2000. Rates before 1991 were obtained from the same sources initially used for Canada (Houghton et al., 1983; Houghton, 1999).

2.2.3. China. A recent analysis of China divided the country into six regions and reconstructed changes in forest area between 1700 and 2000. For three regions (the northeast, northwest and eastern plain), historic rates of cropland expansion and forest loss were reasonably well documented, at least qualitatively. For the north, southeast and southwest, on the other hand, early and late scenarios were constructed to bound possible histories of deforestation. Other aspects of this analysis are discussed below.

Outside the tropics, rates of deforestation and reforestation have been low in recent decades. Large areas are annually logged, and areas reforested and afforested are generally not distinguished in developed countries (FAO, 2000).

3. Results

Globally, the long-term flux of carbon from changes in land use (1850–2000) released 156 PgC to the atmosphere, about 60% of it from the tropics (Table 2). Average annual fluxes during the 1980s and 1990s were 2.0 and 2.2 PgC yr^{-1}, respectively, dominated by releases of carbon from tropical deforestation. Although the average annual flux for the 1990s was higher than for the 1980s, it was generally declining over most of the 1990s (Fig. 1).

The revisions and re-analyses summarized here decreased the earlier estimate of emissions (Houghton,

Table 2. *Average annual flux of carbon to the atmosphere from changes in land use (PgC yr^{-1})*[a]

Region	1850–2000	1980–1989	1990–1999
Tropical Asia	48	0.88 ± 0.5	1.09 ± 0.5
Tropical America	37	0.77 ± 0.3	0.75 ± 0.3
Tropical Africa	13	0.28 ± 0.2	0.35 ± 0.2
Subtotal tropics	98	1.93 ± 0.6	2.20 ± 0.6
Canada	5	0.03 ± 0.2	0.03 ± 0.2
US	7	-0.12 ± 0.2	-0.11[b] ± 0.2
Europe	5	-0.02 ± 0.2	-0.02[b] ± 0.2
Former Soviet Union	11	0.03 ± 0.2	0.02[b] ± 0.2
China	23	0.11 ± 0.2	0.03 ± 0.2
Pacific developed	4	0.01 ± 0.2	0.00[b] ± 0.2
North Africa & Middle East	3	0.02 ± 0.2	0.02[b] ± 0.2
Subtotal non-tropics	58	0.06 ± 0.5	-0.02 ± 0.5
Global total	156	1.99 ± 0.8	2.18 ± 0.8

[a]Negative values indicate an accumulation of carbon on land.
[b]Annual flux through the 1990s assumed to have remained the same as calculated for the year 1990.

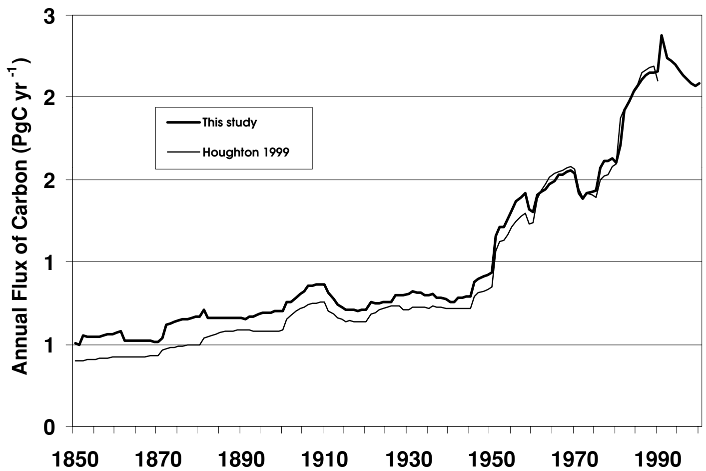

Fig. 1. Annual flux of carbon from global changes in land use and land management. Positive values indicate a release to the atmosphere.

1999) in tropical America (by 0.22 PgC yr^{-1} in the 1980s) and increased it (by 0.20 PgC yr^{-1}) in tropical Asia. Revisions outside the tropics increased the sink by about 0.1 PgC yr^{-1} in North America and increased the estimated source by 0.05 PgC yr^{-1} in China. Thus, both in and outside the tropics revisions to the estimated flux of carbon for the 1980s were largely offsetting.

The average annual net flux of carbon from the tropics during the 1990s (2.2 PgC yr^{-1}) was slightly higher than in the 1980s (1.9 PgC yr^{-1}) (Table 2). Outside the tropics, the average net annual flux of carbon decreased from a source of 0.06 PgC yr^{-1} during the 1980s to a net sink of 0.02 PgC yr^{-1} during the 1990s. According to the revisions described here, changes in land use were responsible for carbon sinks in North America and Europe during the 1990s and for sources in the other non-tropical regions.

The errors shown in Table 2 were estimated based on the experience of the author. They are large enough to include the variations found in re-analyses of regions. They are approximately ±50% for tropical regions, where annual emissions are substantial. Outside the tropics, percentage errors are inappropriate because the fluxes are near zero.

The disturbance and recovery processes determining fluxes of carbon are substantially different inside and outside the tropics (Table 3). At present, the tropics are characterized by high rates of deforestation. The conversion of forests to non-forests involves a large loss of carbon, even though much of the loss occurs in the years following deforestation. In contrast, the fluxes of carbon to and from temperate-zone and boreal lands are dominated by rotational processes, for example, logging and subsequent regrowth. Outright clearing of forests for new agricultural land is small. The losses of carbon from decay of wood products and slash (woody debris generated as a result of harvest) are largely offset by the accumulation of carbon in regrowing forests (reforestation and regrowth following harvest) (Table 3). Rotational processes are just as common in the tropics as in temperate zones (even more so because shifting cultivation as well as logging are common in the tropics), but the net flux of carbon from these activities is dwarfed in the tropics by the large releases resulting from permanent deforestation. Differences between the totals in Tables 2 and 3 are the result of rounding errors.

4. Discussion

4.1. Comparisons with other estimates of land-use change

The revisions described in this paper increased a previous global estimate (Houghton, 1999) from 124 to 134 PgC for the period 1850–1990, most of the increase appearing before 1960 (Fig. 1). Revisions were as large as 0.3 PgC yr^{-1} in individual regions (Latin America during the 1980s; China during the 1950s), but were largely offsetting globally. The global

Table 3. *Estimates of the annual sources (+) and sinks (−) of carbon during the 1990s (TgC yr^{-1}) resulting from different types of land-use change and management*

Activity	Tropical regions	Temperate and boreal zones	Globe
1. Deforestation	2110[a]	130	2240
2. Afforestation	−100	−80[b]	−180
3. Reforestation (agricultural abandonment)	0[a]	−60	−60
4. Harvest/management	190	120	310
(a) Products	200	390	590
(b) Slash	420	420	840
(c) Regrowth	−430	−690	−1120
5. Fire suppression[c]	0	−30	−30
6. Non-forests			
(a) Agricultural soils[d]	0	20	20
(b) Woody encroachment[c]	0	−60	−60
Total	2200	40	2240

[a]Only the net effect of shifting cultivation is included here. The gross fluxes from repeated clearing and abandonment are not included.
[b]Areas of plantation forests are not generally reported in developed countries. This estimates includes only China's plantations.
[c]Probably an underestimate. The estimate is for the US only, and similar values may apply in South America, Australia and elsewhere.
[d]These values include loss of soil carbon resulting from cultivation of new lands; they do not include accumulations of carbon that may have resulted from recent agricultural practices.

annual flux declined during the 1990s but averaged 0.2 PgC yr^{-1} higher than in the previous decade.

Other recent analyses of the flux of carbon from land-use change give results that bound the results reported here (Table 4), although differences in the processes and regions included make comparisons somewhat misleading. The estimates of flux for the 1980s by McGuire et al. (2001), Houghton (1999) and this study, for example, are global, while the estimate by Fearnside (2000) includes only the tropics. The source estimated by McGuire et al. (2001) is low because it does not include either the harvest of wood or the clearing of forests for pastures, both of which contributed to the net global source calculated by Houghton (1999) and this study (Table 3). On the other hand, the average annual release of carbon attributed here to changes in the area of croplands (1.2 PgC yr^{-1} for the 1980s) is higher than the estimate found by McGuire et al. (0.8 PgC yr^{-1}) (Fig. 2). The difference reflects uncertainties in the data used to reconstruct changes in cropland area and to define the carbon stocks of the ecosystems cleared.

Table 4. *Estimates of the average annual flux of carbon in the 1980s from changes in land use (positive values indicate a release of carbon to the atmosphere)*

Flux of carbon (PgC yr^{-1})	Regions included	Reference
0.8[a] (0.6–1.0)	Globe	McGuire et al., 2001
2.4 (1.4–3.4)	Tropics	Fearnside, 2000
2.0 (1.2–2.8)	Globe	Houghton, 1999
1.7	Globe	Houghton, 2000
2.0 (1.2–2.8)	Globe	This study

[a]Croplands only (changes in the area of pastures and harvest of wood were not included).

4.2. *Uncertainties*

Variability in the estimated fluxes of carbon results from two uncertainties: rates of land-use change and the carbon stocks of the ecosystems affected by human activity.

4.2.1. Rates of land-use change. The availability of land-use data, especially historic data, varies by region. Although rates of land-use change are generally more accessible for the last few decades than for earlier years, even recent estimates are often highly variable. In China, for example, the area of croplands is

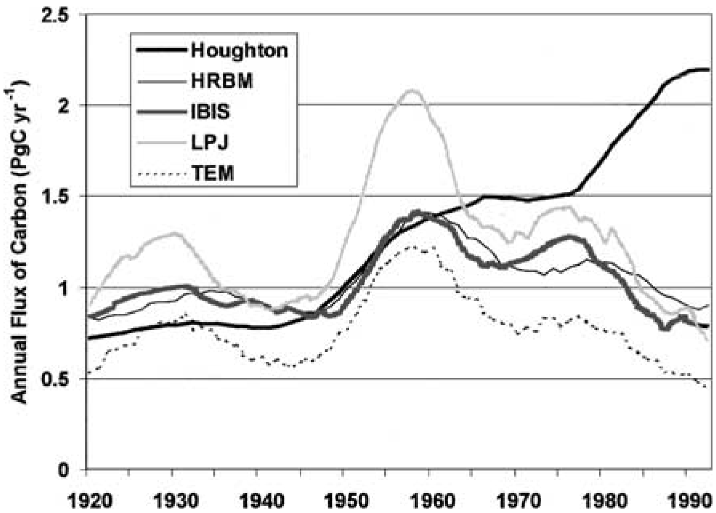

Fig. 2. Estimates of the annual flux of carbon from global changes in croplands. Positive values indicate a release to the atmosphere. Houghton's estimate is from this study; the four other estimates are from terrestrial biosphere models (McGuire et al., 2001).

reported by one source to be increasing (FAO, 2001a) and by other sources to be decreasing (China Agriculture Yearbooks, 1980–1991; US Department of Agriculture, 1992). Furthermore, official reports of cropland areas average 40% lower than areas measured with high-resolution satellite data (Frolking et al., 2002). Despite these uncertainties in cropland area, the changes in croplands in recent years are believed to have had only a small effect on estimated carbon fluxes for China because croplands are converted to and from lands with similar carbon stocks (urban, residential industrial and temporarily fallow lands). Harvests of wood and afforestation are responsible for most of the recent changes in Chinese forests and, hence, are the activities most influential in determining sources and sinks of carbon in the last two decades.

The factor most important in influencing estimates of the current flux of carbon, globally, is the rate of deforestation in the tropics. Variations in the rate determine decadal variations in flux over the last 30 years and, along with estimates of forest biomass, determine the absolute magnitude of emissions. The only estimates of deforestation available for the entire tropics are those provided by the FAO's Forest Resources Assessments (FAO/UNEP, 1981; FAO, 1993, 1997, 2000, 2001b), although these estimates have been criticized (Myers, 1980; Grainger, 1984; Tucker and Townshend, 2000).

The FAO Forest Resource Assessments have used more than one method to estimate changes in the area forests. The older method is based on a combination of national reporting to the FAO and FAO country-level expertise. No estimate of error is available for this approach. Since 1990 the FAO has also used satellite data to sample changes in forest area (FAO, 1996). The sampling was based on 117 Landsat scenes distributed over the major tropical regions (10% sampling of forest area). Sampling was designed to yield broad regional estimates of deforestation, not estimates for individual countries, so comparisons with independent country-level estimates are inappropriate. On the other hand, the sampling design enabled an error to be calculated for regional estimates of deforestation. The method is subject to large errors if the distribution of deforestation is clumped, as Tucker and Townshend (2000) found for Bolivia, Colombia and Peru. The clumped nature of deforestation rates in these countries suggested that a sample including about 80% of the forest area (not 10%) was required for an accuracy within ±20%.

For the few tropical countries where rates of deforestation have been determined independently of the FAO, estimates have often been lower, in a few cases very much lower (Table 5). Most of these individual estimates are unofficial, provisional estimates reviewed by Houghton and Ramakrishna (1999). They may be biased toward low emissions. Ironically, the estimates

Table 5. *Estimates of rates of deforestation (10^3 ha yr^{-1}) in a selection of tropical countries*

Country	FAO (1993)	Other estimate	Source
Bolivia	625	100	Unofficial emissions inventory
		153	Steininger et al., 2001
Brazil	3671	1120–2708	Houghton et al., 2000b[a]
Costa Rica[b]	50(2.9%)	>45(4.2%)	Sánchez-Azofeifa et al., 2001
Ethiopia	39	189	Unofficial emissions inventory
Mexico	678	370–858	Unofficial emissions inventory
Venezuela	599	517	Unofficial emissions inventory
Zimbabwe	61	10	Unofficial emissions inventory

[a]Brazilian Space Agency; Legal Amazonia only.
[b]The absolute rate of deforestation in Costa Rica (Sánchez-Azofeifa et al., 2001) was based on an analysis that included only about 50% of the country's forest area and thus probably underestimates the total rate. The annual percentages of the respective forest areas lost are shown in parentheses, suggesting that the FAO estimate is low in this comparison.

from the FAO are also based on national surveys (not remote sensing), and raise the question: How can a national response to the FAO be so different from an independent national estimate? Are the different estimates determined by different agencies within the same country? The FAO is reluctant to give out the names and addresses of the agencies reporting to them. Three of the estimates in Table 5 are based on analyses of Landsat data by third parties, and two of them show rates lower than reported by FAO. Satellite data may miss some of the small patches of clearing, but probably more important is the fact that these remote sensing studies often do not include all of a country's forests, or that they apply to different dates. As a result, some of the differences between estimates may be exaggerated. Nevertheless, uncertainty in the rates of tropical deforestation and afforestation over the last 30 years contributes more to the variability of flux estimates than any other factor. The need for a systematic sampling large enough to determine rates of change to within about 25% is crucial. Two- to three-year averages would probably suffice and would cost considerably less than annual determinations.

One further caution needs to be considered with respect to reconstructing changes in land use. For many regions of the world, if the areas of different land uses are inventoried at all, the inventories are often limited to croplands and, to a lesser extent, pastures. Rarely are there accurate measurements and records of forest area, where changes have the greatest effect on carbon storage. For this reason, analyses of land-use change have generally relied on reported changes in the area and distribution of croplands and pastures to infer changes in the area of forests. In some regions, however, changes in croplands and pastures do not account for changes in forests. During the 1980s, for example, the net loss of forest area in the tropics was about twice as large as the net increase in croplands and pastures (FAO, 1990; Houghton, 1994).

The inability of agricultural increases to explain forest losses has also been observed in China, where the long-term loss of forests is estimated to have been more than twice the current area of croplands (this work). Because most pastures are believed to have come from non-forested lands in China, something besides the expansion of croplands and pastures must explain the excessive loss of forests. The most likely explanation is that substantial areas of farmland have been abandoned, yet have not returned to forests or have not been reported as forests, either because the lands have become degraded or because they are repeatedly burned (Marks, 1998) or cycled back into agriculture. Whatever the mechanisms, the cautionary point is that those changes in land use best documented (croplands and pastures) may be insufficient for reconstructing changes in forest area and, thus, changes in terrestrial carbon.

The difference between net changes in forest area and net changes in agricultural area may also help explain the difference in estimated fluxes of carbon attributed to croplands (Fig. 2). The change in cropland areas was estimated in this study by distributing the rate of deforestation (FAO, 2000) among land uses in proportion to net changes in cropland, pasture, and other areas (FAO, 2001a), thus yielding a greater rate of increase in cropland areas than reported by FAO (2001a). In contrast, the modeling analyses included in the study by McGuire et al. (2001) used net changes in cropland areas (Ramankutty and Foley, 1999) to calculate flux. The different estimates of flux, therefore, result from different assumptions about the dynamics of croplands. This analysis assumed that large areas of cropland are abandoned and replaced with new lands cleared from forests. The resulting flux is larger than one calculated from the net increase in cropland areas, which misses abandonment and additional, simultaneous deforestation.

4.2.2. Carbon stocks. Apart from uncertain rates of deforestation and reforestation, the carbon stocks of ecosystems add variability to estimates of carbon flux in at least two respects. First, the carbon stocks of the ecosystems cleared, harvested, burned, or otherwise affected by management are known only approximately. Second, changes in these carbon stocks as a result of human activity (the fractions of biomass harvested and left alive and dead on site, and the rates of decay and regowth that follow a change in land use or management) are also uncertain.

The first type of uncertainty, carbon stocks of the ecosystems affected by human activity, has the potential to be much reduced if the geographic location of changes in land use can be determined. The biomass of the lands actually affected allows a more precise estimate of carbon flux to be obtained than assuming an average biomass value for the region. Spatial detail may be obtained with satellite data, but it is difficult with historical, largely tabular, data. Several recent studies have developed spatial data for long-term changes in croplands (Ramankutty and Foley, 1999; Frolking et al., 2002), croplands and pastures (Klein Goldewijk, 2001), and land cover (Hurtt et al., 2001). Many estimates of the spatial distribution of biomass and soil carbon also exist, but the estimates are variable. A recent comparison of seven estimates of biomass in Amazonian forests, for example, showed little agreement in either total biomass for the region or its distribution (Houghton et al., 2001). On the other hand, differences in biomass between classes of moist tropical forests are small relative to differences in biomass between forests and non-forests. Thus a simple spatial classification, distinguishing between forests and non-forests, allows a more precise estimate of carbon flux than changes in land use with no indication of the ecosystems affected.

The second type of uncertainty, changes in carbon stocks following land-use change or management, may be of less importance in affecting estimates of carbon flux because errors are often cancelled. For example, the regional uptake of carbon in growing forests is a function of growth rates per hectare and the areas regrowing. If rates of growth are overestimated, the area of secondary forests will be small (because more forests will have recovered), and the net flux will be similar to the flux calculated with lower rates of regrowth (over larger areas still recovering). The same is generally true for rates of decay: the higher the rate, the shorter the period over which decay occurs. As long as rates of land-use change are not fluctuating significantly, errors in the modeled rates of decay and regrowth have a small effect on the calculated annual flux of carbon. In regions where the net flux is near zero, however, the small effect is likely to be important. Furthermore, if forests continue to accumulate carbon, even at a low rate after 50–200 years (by which time we assume they are fully grown), the accumulation may be significant if large areas are involved. How long forests continue to accumulate carbon and at what rates are not well known. Alternatively, we can obtain from our analyses the proportions of primary and secondary forest at the end of a simulation. Large areas of primary forest suggest that we have underestimated past rates of disturbance or overestimated recovery rates, in either case underestimating the current sink. Results suggest that we may have underestimated sinks in some regions.

Finally, the changes in land use and management considered in this analysis did not include all types of land management. The analysis ignored forms of forest or agricultural management other than the recovery of forests following harvest or agricultural abandonment (i.e. changes in area). The analysis did not include, for example, changes in tree species or varieties, thinning, silviculture, use of fertilizers or conservation tillage, any of which may increase the amount of carbon held on land.

4.3. Implications for the terrestrial carbon sink

The flux of carbon in the 1990s calculated to have resulted from land-use change and management is larger than initially estimated by Houghton (2000) and reported in the Third Assessment Report of the IPCC (Prentice et al., 2001). Other recent changes in our understanding of the global carbon balance, as a result of accounting for the outgassing of O_2 from oceans (Plattner et al., 2002), suggest that the residual terrestrial sink [the difference between the net terrestrial flux (inferred from atmospheric O_2 and CO_2 data) and

Table 6. *Global carbon budgets for the 1980s and 1990s (PgC yr^{-1})*[a]

	1980s	1990s
Fossil fuel emissions[b]	5.4 ± 0.3	6.3 ± 0.4
Atmospheric increase[b]	3.3 ± 0.1	3.2 ± 0.2
Oceanic uptake[c]	−1.7 ± 0.6	−2.4 ± 0.7
Net terrestrial flux[c]	−0.4 ± 0.7	−0.7 ± 0.8
Land-use change[d]	2.0 ± 0.8	2.2 ± 0.8
Residual 'terrestrial' flux	−2.4 ± 1.1	−2.9 ± 1.1

[a]Negative values indicate a withdrawal of CO_2 from the atmosphere.
[b]From Prentice et al. (2001).
[c]From Plattner et al. (2002).
[d]This study.

the land-use flux] averaged 2.4 ± 1.1 PgC yr^{-1} during the 1980s and 2.9 ± 1.1 PgC yr^{-1} during the 1990s (Table 6). The difference between decades in both the net and the residual terrestrial flux is smaller than summarized by Prentice et al. (2001), although the residual sink of 2.4–2.9 PgC yr^{-1} is clearly significant.

Given the recent revisions to the estimated oceanic and terrestrial sinks (the latter is now half as large) (0.7 PgC yr^{-1}, rather than 1.4 PgC yr^{-1}) (Plattner et al., 2002), it might be appropriate to drop the word *terrestrial* from the term *residual terrestrial sink* and refer to it as the *residual sink*. Errors in the estimated oceanic uptake of carbon affect the magnitude of the residual sink as much as errors in land-use change.

To the extent that the residual sink is terrestrial, it exists in both northern mid-latitudes and the tropics. In northern mid-latitudes the sink attributable to the recovery of forests from past changes in land use (0.02 ± 0.5 PgC yr^{-1}) is much less than the net terrestrial flux inferred from inverse calculations with atmospheric data and models (1.6–3.2 PgC yr^{-1}) (Gurney et al., 2002) (Table 7). Part of the difference may be explained by the observation that ecosystems other than forests are significant sinks for carbon (Houghton et al., 1999; Pacala et al., 2001). It is also possible that the accumulation of carbon below ground, not directly measured in forest inventories, can account for the difference in estimates. However, the few studies that have measured the accumulation of carbon in forest soils have consistently found soils to account for only a small fraction (5–15%) of measured ecosystem sinks (Gaudinski et al., 2000; Barford et al., 2001; Schlesinger and Lichter, 2001). Thus, despite the fact that the world's soils hold two to three times more carbon than biomass, there is no evidence yet that they account for much of the residual sink.

Forest inventories show a carbon sink in northern forests (0.6–0.7 PgC yr^{-1}) (Goodale et al., 2002) intermediate between estimates based on inverse calculations with atmospheric data and analyses of land-use change (Table 7). Again, accounting for non-forest ecosystems might reduce the difference between the results of inventories and atmospheric analyses. With respect to the difference between forest inventories and land-use change, a regional comparison suggests that the recovery of forests from land-use change may either over- or underestimate the sinks measured in forest inventories (Table 8). In Canada and Russia, the carbon sink calculated for forests recovering from harvests (land-use change) is greater than the measured sink. The difference could be error, but it is consistent with the fact that fires and insect damage increased in these regions during the 1980s and thus converted some of the boreal forests from sinks to sources (Kurz and Apps, 1999). These sources would not be counted in the analysis of land-use change because natural disturbances were ignored. In time, recovery from

Table 7. *Terrestrial sources (+) and sinks (−) of carbon (PgC yr^{-1}) estimated by different methods*

Region	Analysis of land-use change (this study) (1990s)	Inversions based on atmospheric data and models (Gurney et al., 2002) (1992–1996)	Forest inventories (Goodale et al., 2002) (∼1990)
Globe	2.2 (±0.8)	−1.4 (±0.8)	
Tropics	2.2 (±0.8)	1.2 (±1.2)	
North	−0.02 (±0.5)	−2.4 (±0.8)	−0.65 (±0.05)
South	0.02 (+0.2)	−0.2 (±0.6)	

Table 8. *Annual net changes in the living vegetation of forests (TgC yr^{-1}) in northern mid-latitude regions around the year 1990*[a]

Region	Land-Use Change[b]	Forest Inventory[c]	Sink from land-use change relative to inventoried sink
Canada	−25	40	65 (larger)
USA	−35	−110	75 (smaller)
Russia	−55	40	95 (larger)
China	75	−40	115 (smaller)
Europe	−20	−90	70 (smaller)
Total	−60[d]	−160	

[a]Negative values indicate an increase in carbon stocks (that is, a terrestrial sink).
[b]This study.
[c]From Goodale et al. (2002).
[d]The sink of 60 TgC yr^{-1} in the living biomass of forests is different from the values appearing in Tables 2 and 3, which include changes in the pools of dead plant material, wood products and forest soils as well as living biomass.

these natural disturbances would be expected to increase the sink above that calculated on the basis of harvests, alone, but at present the sources from fire and insect damage exceed the net flux associated with harvest and regrowth.

In the three other regions (Table 8), changes in land use show a smaller sink in trees than measured in forest inventories. If the results are not simply a reflection of error, the failure of past changes in land use to explain the measured sink suggests that factors not considered in the analysis have enhanced the storage of carbon in forests. Such factors include past natural disturbances, more subtle forms of management than recovery from harvest and agricultural abandonment (and fire suppression in the US), and environmental changes that may have enhanced forest growth. Analysis of forest inventory data from five states in the US led Caspersen et al. (2000) to conclude that very little of the observed accumulation of carbon in trees could be attributed to enhanced growth. Instead, it was largely explained by recovery from earlier disturbance. The lack of a significant growth response is consistent with recent findings that CO_2 fertilization may be short lived in forests (Oren et al., 2001, Schlesinger and Lichter, 2001).

It remains unclear whether the different estimates of flux from land-use change and inventories are real or the result of errors and omissions. The differences are small, generally less than 0.1 PgC yr^{-1} in any region. As discussed above, the likely errors and omissions in this analysis include rates of forest growth, natural disturbances and many types of management (Spiecker et al., 1996). These possibilities need to be addressed in future analyses.

The same uncertainties apply to the tropics, where the errors are larger. Changes in land use yield smaller sinks (or larger sources) than those inferred from inversion studies (Table 7). The difference suggests the existence of a tropical sink (unrelated to land-use change) large enough to offset at least some of the emissions from deforestation. Because of the increasing importance of human activity in the region, it seems unlikely that the sink would be caused by forests recovering from past disturbances not already included in analyses of land-use change (Table 3). There is no evidence, for example, that rates of natural disturbance are less now than in the past, so that large areas in the tropics are now recovering. However, measurement of CO_2 flux by eddy covariance suggests that undisturbed tropical forests in the Amazon may be a net carbon sink (Grace et al., 1995, Malhi et al., 1998). The rates of accumulation are larger than would be expected for recovered forests and suggest that the rates may be enhanced. However, a new analysis of CO_2 in rivers suggests that much of the forest uptake of carbon is offset by releases downstream, so that undisturbed forests are nearly neutral with respect to carbon (Richey et al., 2002).

Estimates of carbon exchange in the tropics vary considerably. On the one hand, analyses of land-use change consistently find reductions in forest biomass, implying carbon sources (Flint and Richards, 1994; Gaston et al., 1998; Houghton and Hackler, 1999). On the other hand, repeated measurements of forest biomass seem to show an accumulation of carbon in some undisturbed forests (Phillips et al., 1998), although the findings have been attributed to artifacts of measurement (Clark, 2002). It is possible, of course, that both increases and decreases in biomass are occurring simultaneously in different forests. The challenge is to identify the mechanisms. The distribution of people throughout most forest lands suggests that relatively little of the tropics has escaped disturbance from human activity. And, because rates of harvest and burning have generally increased over the last 50 years, the net effect of human disturbance and subsequent recovery has been to reduce carbon stocks. Clearly, there are exceptions, such as in Puerto Rico, where forests have grown back on abandoned farmlands. Overall, however, the trend is a loss of forests

(Table 1) and probably a loss of carbon from within forests as well.

At present, the results from numerous independent measurements cannot distinguish between two mutually exclusive paradigms: large sources of carbon from deforestation, offset by enhanced growth (in undisturbed forests), or more moderate sources of carbon than calculated here, and natural forests close to neutral with respect to carbon. Enhanced rates of plant growth cannot be ruled out as an explanation for apparent sinks in either the tropics or mid-latitude lands, but it is possible that the current sink is entirely the result of recovery from earlier disturbances, anthropogenic and natural.

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